SAND22-1147R
LDRD PROJECT NUMBER: 22-1147
LDRD PROJECT TITLE: Lossless Quantum Hard-Drive Memory Using Parity-Time Symmetry
PROJECT TEAM MEMBERS:
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ABSTRACT:

We theoretically studied the feasibility of building a long-term read-write quantum memory using the principle of parity-time (PT) symmetry, which has already been demonstrated for classical systems. The design consisted of a two-resonator system. Although both resonators would feature intrinsic loss, the goal was to apply a driving signal to one of the resonators such that it would become an amplifying subsystem, with a gain rate equal and opposite to the loss rate of the lossy resonator. Consequently, the loss and gain probabilities in the overall system would cancel out, yielding a closed quantum system. Upon performing detailed calculations on the impact of a driving signal on a lossy resonator, our results demonstrated that an amplifying resonator is physically unfeasible, thus forestalling the possibility of PT-symmetric quantum storage. Our finding serves to significantly narrow down future research into designing a viable quantum hard drive.

INTRODUCTION AND EXECUTIVE SUMMARY OF RESULTS:

As quantum computing has grown in prominence, a critical necessity for long-term storage of quantum information (qubits) in a read-write memory has arisen. In recent years, the two main ideas that have been proposed for such a long-term quantum memory have been resonators with long phase information lifetime (e.g., mechanical oscillations, known as phonons) and dynamical decoupling (applying periodic pulses to a resonator to neutralize loss). However, the downside of long-phase-information-lifetime memories is that for the required qubit frequency, even phonons, for example, feature a lifetime of less than 1 second [1,2]. Such existing long-lifetime modes, therefore, are useful for medium-term buffering applications, but not for long-term storage. Dynamical decoupling, on the other hand, features two important downsides: first, recent studies have demonstrated significant losses [3,4], and second, more fundamentally, this method cannot simultaneously stabilize the bit-flip and phase-flip errors.

In this project, we thus focused on using the principle of parity-time (PT) symmetry to build a long-term read-write quantum memory, with a storage time of over 10 minutes. In recent years, PT symmetry has gained prominence by presenting lossless data storage in a partly lossy system, implying that a quantum system can be closed to the environment even if individual components

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are open [5]. The key idea is that if two components, one lossy and one amplifying, are coupled such that the loss rate in the former is cancelled out by the gain rate in the latter, and if the interaction rate between the two components is greater than the loss/gain rate of each, then the overall system will be effectively closed. Although such systems have previously been demonstrated in the classical and semi-classical regime for a large excitation number [6,7], demonstration in the single-qubit regime has been elusive.

We hypothesized that PT-symmetric storage of a single qubit (storage time > 10 minutes), would be achievable given a coupled two-resonator system, where one would be a regular lossy resonator, while the other would be converted to an amplifying resonator by applying a driving signal to neutralize the loss and instead generate intrinsic gain. Our quantitative methods showed that no drive signal can give rise to an amplifying resonator functioning as the time-reversed version of a lossy resonator. Therefore, we showed that PT-symmetric quantum storage is not feasible. Our research serves to significantly narrow future research in long-term quantum storage.

Please see the Addendum for more information.

DETAILED DESCRIPTION OF RESEARCH AND DEVELOPMENT AND METHODOLOGY:

This was a theory project, based on quantitative modeling and simulation. The goal and hypothesis are summarized in Slide 2 of the Addendum, along with a figure depicting the design. The shortcomings of previous methods, specifically the use of a single long-phase-information-lifetime resonator or application of dynamical decoupling, are summarized in Slide 3 of the Addendum. The project plan was divided into 5 steps, as summarized in Slide 1 of the Addendum and described in more detail as follows:

The first step would be to use the quantum master equation to solve for the driving signal required to convert a lossy resonator to an amplifying resonator, such that this resonator would function as the time-reversed version of a regular lossy resonator. Specifically, we would employ the SLH (scattering-Lindblad-Hamiltonian) theory [8,9], where interactions within a system are modeled by a Hamiltonian and losses to the environment are modeled by a Lindbladian.

If an amplifying resonator were successfully demonstrated, the second step would be to determine how to couple the lossy resonator with the amplifying resonator. The key requirement here was to determine a physical coupling method such that the interaction rate would exceed the intrinsic loss/gain rate of each resonator. If this condition were satisfied, the overall system would then be in one of two composite quantum states, each with zero energetic spectral broadening (indicating a completely closed overall system), whereas if the intrinsic loss/gain rate of each resonator were greater than the interaction rate, then the two states would merge into a single state with spectral broadening (indicating an open, lossy overall system). Here, our initial focus would be on long-phase-information-lifetime systems such as acoustic resonators (phonons) or superconducting circuits (transmons), since the low intrinsic loss/gain rate of each resonator would provide significant leeway in setting a resonator-to-resonator interaction rate.

If successful, this would complete the successful demonstration of PT-symmetric quantum storage. The third step would then be to determine an optimal read-write protocol for the system. Specifically, we would expand on our previous work in absorbing a propagating qubit into a stationary resonator by dynamically tuning the output coupling rate between the resonator and the quantum input-output channel [10]. The design would include a quantum input-output channel connected to each resonator with a dynamically tunable output coupling rate. Here, we would make use of the superposition weight assigned to each resonator in the composite PT-symmetric state. Specifically, the relative weight includes a phase, which is a function of the ratio between the inter-resonator interaction rate and the loss/gain rate of each resonator. The effect of this phase is to stagger the physical dynamics of one resonator in time relative to the other. Consequently, in order to absorb an incoming qubit into this PT-symmetric system, the requirement would be to simultaneously tune the output coupling rates of both resonators, staggering the temporal profile of one relative to the other based on the superposition phase.

A complication during the writing process could arise from the fact that the PT-symmetric states are not fully orthogonal to each other (i.e., there is non-zero overlap between the states) [5], potentially resulting in a fraction of the quantum input being stored in an undesired state. As such, an important aspect of designing the read-write protocol would be to analyze any tradeoff between the storage time and the read-write fidelity, with the goal of ensuring a storage time of at least 10 minutes.

Successfully demonstrating the read-write protocol would demonstrate a PT-symmetric quantum hard drive in an idealized environment. However, a realistic environment features quantum noise. The fourth step would therefore be to optimize the overall system to minimize the effect of quantum noise. As in the first step, we would use the scattering-Lindblad-Hamiltonian (SLH) theory, this time to model an input from the bath. The task would be to minimize the potential noise sources and, if any noise persisted, to determine how to expand the hardware architecture (e.g., by adding more resonators) to minimize noise effects.

Finally, if the feasibility of a PT-symmetric read-write quantum memory were successfully demonstrated (theoretically) in an environment with realistic levels of optimal noise, then the fifth step would be to design the experiment itself and to write the algorithm for dynamically tuning the resonator output coupling rates to achieve the read-write functionality. The detailed specifications for the experimental setup and the automated read-write algorithm would be used in the lab in a follow-on project.

RESULTS AND DISCUSSION:

A no-go result was achieved for our hypothesis in the first step. The findings are summarized in Slides 1 and 3 of the Addendum, and described in more detail as follows:

The goal in this step was to use the quantum master equation, specifically the scattering-Lindblad-Hamiltonian (SLH) theory, to determine whether applying a classical drive signal to a lossy resonator would yield an amplifying resonator, for which the time-evolution is the reverse of a regular lossy resonator in isolation. The interaction between the driving signal and the resonator was modeled by a displacement Hamiltonian, whereas the inherent intrinsic loss of the resonator was modeled by a Lindbladian. The rate of change of the individual terms in the density matrix representing the composite system were quantitatively analyzed. If the time-evolution of all terms for a resonator under intrinsic loss and a driving signal of a particular intensity matched the time-evolution of the density matrix terms for an equivalent amplifying resonator with an intrinsic gain rate (of an equal magnitude as the original intrinsic loss rate), then the time-reversal condition would be satisfied.

During the analysis of the density matrix, a fundamental problem was discovered regarding pure-state vs. mixed-state dynamics. For insight, recall that a single resonator is a two-dimensional Hilbert space, with the basis states being |0> (i.e., vacuum) and |1> (i.e., singly-occupied). We label the diagonal density matrix elements as $\rho_{0,0}$ (corresponding to the vacuum population) and $\rho_{1,1}$ (corresponding to the singly-occupied population), and we label the off-diagonal elements as $\rho_{1,0}$ and $\rho_{0,1}$. The off-diagonal elements serve as a measurement of the purity of the |0> and |1> superposition. As a regular lossy resonator evolves in time, $\rho_{1,1}$ decreases and $\rho_{0,0}$ increases, while the off-diagonal elements evolve as if $\rho_{0,0}$ were constant. This can be interpreted as follows: For the original pure state, the superposition weight shifts from |1> to |0>, while at the same time, the probability that the system is in that state decreases. At the same time, a new vacuum pure state (entirely |0>) is created, with increasing probability that the system is in that state. The system is now in a mixed state, a consequence of a quantum jump from the original pure state to the new pure |0> state.

To time-reverse these dynamics, therefore, a quantum jump from |0> to either |1> or a superposition of |0> and |1> is necessary. However, a classical driving signal maintains the system in a pure state, with the off-diagonal density matrix elements $\rho_{1,0}$ and $\rho_{0,1}$ evolving in tandem with the on-diagonal elements $\rho_{0,0}$ and $\rho_{1,1}$. This was manifested in our calculations by the fact that whereas the off-diagonal density matrix terms would remain constant in an amplifying resonator, the displacement Hamiltonian representing the classical driving field yielded a change in these off-diagonal terms.

This led to an even more fundamental discovery. When analyzing the diagonal terms in the density matrix, we found that the second time-derivative of $\rho_{1,1}$ is negative rather than positive. This implies that as the occupation probability of the resonator increases, the absorption probability decreases. However, in order to time-reverse the dynamics of a lossy resonator, the absorption probability must increase with the occupation probability. Our results thus concretely demonstrated that an amplifying resonator, defined as a resonator with dynamics time-reversed relative to a lossy resonator, is not physically feasible.

As such, we theoretically demonstrated that PT-symmetric storage is unfeasible in the quantum regime. This stands in contrast to classical bosonic systems, where PT-symmetric storage has recently been experimentally demonstrated [6,7]. The contradiction can be explained as follows: A classical system features coherent states, consisting of superpositions of multiple excitation numbers, in a regime with unlimited excitation number. Consequently, an absorption rate that increases with the average excitation number is physically achievable. However, for a two-level quantum system, an absorption rate increasing with the occupation probability is intrinsically unphysical due to the saturation effect.

Our no-go finding for our hypothesis serves to significantly narrow down future research in designing a viable quantum hard drive. The key lesson learned was the importance of maximizing team size early in a project and meeting regularly to discuss ideas, even for theory tasks that can be seemingly accomplished by only 1 or 2 individuals. In our case, maximizing team size accelerated the confirmation of the no-go finding and gave us a head start on researching alternative plans for designing a long-term quantum memory.

ANTICIPATED OUTCOMES AND IMPACTS:

The anticipated outcomes and impacts are summarized in Slides 4-6 of the Addendum. A more detailed explanation follows:

The goal of building a long-term read-write quantum memory aligns clearly with the Quantum Information Science (QIS) strategy at Sandia. This is because a key goal in the QIS strategy is heterogeneous integration of new capabilities to hybrid quantum devices. A viable quantum hard drive would qubit fidelity. To this end, a long-term quantum memory would ensure high storage fidelity without the need for significant error correction overhead. The project also promotes the aims of the Computing and Information Science (CIS) and Nanodevices and Microsystems (NM)

LDRD Research Foundations by contributing to the future of quantum computing and developing a heterogeneously-integrated system, respectively.

The key outcome of our finding that PT-symmetric quantum storage is physically unfeasible is to significantly narrow down future research in designing a hard drive for quantum computers. As a follow-on project, our plan is to study the feasibility of using the topological edge state of a *p*-wave superconducting nanowire (also known as a Majorana zero mode) as a lossless read-write quantum memory. This type of superconducting nanowire arises when a regular (*s*-wave) superconducting material is brought in proximity to a semiconducting nanowire [11]. The key advantage of using a Majorana zero mode is its degeneracy (i.e., the occupied Majorana state has the same energy as the vacuum state) [12,13]. Intuitively, this would strongly suppress spontaneous emission from the occupied state to the vacuum state, since such an emission process could not conserve energy.

The main challenges in such a project would be to determine how to encode the phase of a qubit in the Majorana zero mode, as well as how to transduce a qubit from a non-degenerate (energy-separated) mode to the degenerate Majorana mode. Regarding the latter, one possible idea is to temporarily couple the Majorana mode to a quantum dot while writing quantum information into or reading quantum information out of the long-term memory. If the quantum dot is degenerate with the Majorana mode, it has been theoretically shown that the coupling between the two opens a hybridization gap [14]. Recently, we designed an ultra-high-precision microwave photon detector using dot-Majorana coupling [15], and our results provide a clear experimental path for opening a ~5-GHz frequency gap (approximately the general qubit frequency) using this coupling mechanism, as well as a means of tuning the coupling strength by adjusting the height of the potential energy barrier between the dot and the Majorana mode.

For this follow-on project, we plan to collaborate with Sandia experimentalist Wei Pan (8342), with whom we have worked with extensively on designing photon detectors from topological superconducting materials [15,16]. We also plan to build partnerships with external academic experimentalists, particularly those specializing in topological materials in cryogenic settings.

There are two planned publications stemming from this project. In the shorter term, we plan to publish a paper on the unfeasibility of PT-symmetric quantum storage, due to the physical impossibility of building an amplifying resonator in the quantum regime that time-reverses the dynamics of a lossy resonator. In the longer term, we will publish a paper on encoding a qubit in the Majorana mode and transducing quantum information between the Majorana mode and non-degenerate physical systems (e.g., photons, phonons, or transmons) by temporarily coupling the Majorana mode to a quantum dot. This second paper will likely evolve over the course of the follow-on project.

Finally, this project had a significant impact on staff development, by helping further develop modeling/simulation skills and especially by significantly developing teamwork skills for the PI and all team members. On the financial side, the project supported one postdoc/early-career scientist, at a rate of approximately 0.33 FTE.

CONCLUSION:

We theoretically investigated the prospect of using the principle of parity-time (PT) symmetry to build a long-term read-write quantum memory, a capability critical for a viable quantum computer. Our investigation was stimulated by the shortcomings of other methods proposed in recent years for quantum storage, specifically long-phase-information-lifetime memories and dynamical decoupling.

We hypothesized that PT-symmetric quantum storage would be feasible given a two-resonator system, with a lossy resonator coupled to an amplifying resonator at an interaction rate greater than the loss/gain rate of each resonator individually. Concretely, our success metric was a storage time of over 10 minutes. Our R&D approach consisted of 5 steps, namely using the quantum master equation to determine whether application of a classical drive signal could convert a regular lossy resonator to an amplifying resonator, designing a coupling mechanism between the two resonators to ensure that the coupling rate exceeded the loss/gain rate of each resonator, deriving the optimal read-write protocol for the system by expanding on our previous work in writing quantum information into a single resonator, simulating and minimizing the effect of quantum noise, and designing the experiment and the read-write algorithm.

We achieved a no-go result while working through the first step, indicating that PT-symmetric quantum storage would not be possible since building an amplifying resonator in the quantum regime is not physically feasible. We therefore spent the rest of the project focusing on an alternative means of designing a long-term quantum memory: using a topological edge or surface state. This led to the idea of using the Majorana edge mode of a *p*-wave superconducting nanowire as a platform for hosting qubits over the long term. We plan to pursue this idea both theoretically and experimentally in a follow-on project.

Overall, our result significantly advanced the goal of building a viable quantum hard drive by narrowing down future research in this area. This in turn advanced the quantum information science (QIS) strategy at Sandia, in addition to serving the aims of the Computing and Information Science (CIS) and Nanodevices and Microsystems (NM) LDRD Research Foundations. Furthermore, the project had a major impact on staff development by building modeling/simulation and especially teamwork skills. We hope to harness these skills in the follow-on project and all our other future Sandia projects.

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ADDENDUM:

Please see the following slides.

LABORATORY DIRECTED RESEARCH & DEVELOPMENT
WHERE INNOVATION BEGINS

Lossless Quantum Hard-Drive Memory Using Parity-Time Symmetry
22-1147

PI: Eric Chatterjee (8648)
Team Members: Daniel Soh (8648), Steve Young (1425)
PM: David Reyna (8648)

Purpose, Approach, and Goal

Key goal
Demonstrate theory-feasibility of a PT-symmetric lossless quantum hard drive

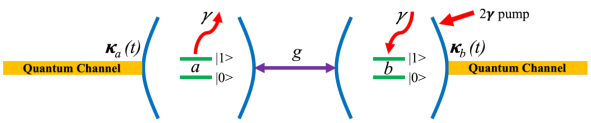
Specific technology gap of conventional quantum memories
- Long-lifetime memories: useful for buffering (<1 sec) but not long-term storage
- Dynamical decoupling: significant loss, cannot simultaneously stabilize bit-flip and phase-flip errors

Hypothesis
A hybrid loss-gain connected system can achieve lossless storage of quantum information if parity-time symmetry is satisfied (physically equivalent resonators, balanced gain/loss)

R&D approach
- Use quantum master equation to solve for amplifying resonator's driving signal
- If previous step is successful, design coupling mechanism between two resonators
- If previous step is successful, derive optimal read-write protocol
- Simulate and minimize quantum noise, potentially adding new components
- If previous 2 steps are successful, design experiment and read-write algorithm

Contribution to Sandia mission
CIS LDRD Foundation, NM LDRD Foundation, Quantum Systems Accelerator (QSA)

Representative Figure



Depiction of basic PT-symmetric system: pair of physically equivalent resonators, with loss probability in one balanced out by gain probability in the other

Key R&D Results and Significance

R&D Summary
- Used quantum master equation to determine necessary classical driving signal
  - First treated amplifying resonator in isolation
  - Lindbladian modeled intrinsic loss to environment, and displacement Hamiltonian modeled effect of classical driving signal
  - Question: Would classical driving signal act as an effectively time-reversed version of intrinsic loss?
- Found that driving signal cannot mimic time-reversal of intrinsic loss
  - Driving signal creates |0> and |1> superposition instead of quantum jump
  - More fundamentally, as probability that resonator is occupied increases, amplifying functionality requires that the probability of absorption also increase (intrinsically unphysical, due to saturation effect in quantum regime)

Result/Follow-on
- Achieved no-go answer after the first step
- Learned that PT-symmetric storage in quantum regime is not possible, since no physical process acting as time-reversal of intrinsic loss exists
- Follow-on: Use topological edge state (Majorana zero mode) of superconducting nanowire as quantum memory

Lessons learned
- Important to maximize team size and meet regularly to share ideas
  - Different team members can bring different experiences that allow them to see problem from different angles, making problem solving much more efficient

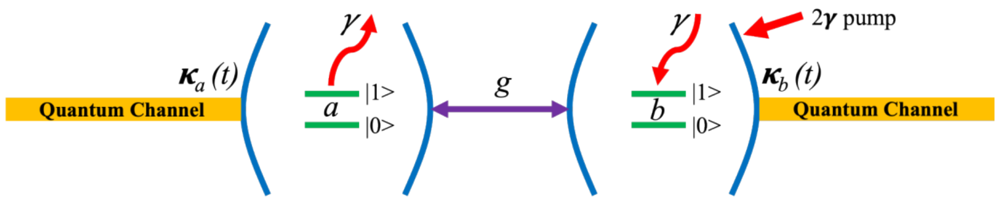
Impact of follow-on plans
- Aligns with Sandia QIS strategy due to heterogenous integration of a critical capability
- Plan to build partnerships with universities and Sandia experimentalists

Publications/Staff Development
- Currently planning paper discussing quantum memory using nanowire topological edge state, and another on the unfeasibility of PT-symmetry in quantum regime
- Built modeling/simulation and especially teamwork abilities, and supported 1 postdoc/early-career staff

LABORATORY DIRECTED RESEARCH & DEVELOPMENT
WHERE INNOVATION BEGINS

R&D Summary (Methods, Results and Discussions)

- **Original goal:** Design a lossless (> 10 min.) quantum memory using parity-time (PT) symmetry
- **Original hypothesis:** PT symmetry, which has been demonstrated in the classical regime, can be applied to the quantum regime as well, through a hybrid loss-gain system satisfying the following conditions:
  - ➢ The lossy and amplifying components must be resonant (same operational frequency)
  - ➢ The loss rate of the lossy component must be balanced out by an equal and opposite gain rate in the amplifying component



R&D Summary (Cont.)

- Shortcomings of previous proposed methods for long-term quantum information storage:
  - **Long-phase-information-lifetime memories:** useful for buffering (< 1 sec), but not long-term storage
  - **Dynamical decoupling:** Cannot simultaneously stabilize phase-flip and bit-flip errors
- Technique used: master equation for open quantum systems
  - Treated amplifying resonator first to check whether effect of classical driving signal on resonator is equivalent to time-reversal of intrinsic loss
  - Used Lindbladian to model intrinsic loss, and Hamiltonian to model effect of classical driving signal
- **Result:** Found that driving signal cannot yield quantum amplification, defined as time-reversal of intrinsic loss
  - Driving signal creates pure-state superposition of unoccupied (|0>) and occupied (|1>) states instead of the required quantum jump from unoccupied to occupied state
  - More fundamentally, amplifying functionality requires that as the occupation probability (i.e. "population") of the resonator increases, the probability that the resonator absorbs an excitation from the driving signal must increase as well (intrinsically unphysical in the quantum regime, due to the saturation effect)
- **Key finding:** PT-symmetric quantum information storage is not possible, since no physical mechanism exists to achieve time-reversed version of intrinsic loss process
  - Serves to narrow down future research in long-term quantum storage

R&D Summary (Cont.)

- **Alternative plan:** Study the feasibility of using topological edge state (Majorana zero mode) of superconducting nanowire as lossless quantum memory
  - **Advantage:** Occupied Majorana state is degenerate (energy-equivalent) with unoccupied state, strongly suppressing spontaneous switching due to photon or phonon emission
  - **Challenge:** Need to determine how to transduce qubit between Majorana mode and other physical platforms (e.g. transmons, photons, phonons)
- **Lesson learned:** Important to maximize team size and meet regularly to share ideas, even for theory tasks that can seemingly be accomplished by one or two people
  - Large number of team members results in problem solving skill sets from a wider variety of sub-fields, making overall analysis process for a project much more efficient

LDRD Project Metrics

Planned Publications

- Planning paper on encoding qubit in Majorana mode and transducing between Majorana and other physical systems
- Also planning paper on unfeasibility of PT symmetry in the quantum regime

Staff Development

- Developed modeling and simulation skills, and especially teamwork abilities, for PI and all team members
- Supported 1 postdoc/early-career scientist
  - ~0.33 FTE (with respect to the full fiscal year)

LABORATORY DIRECTED RESEARCH & DEVELOPMENT

WHERE INNOVATION BEGINS

Project Legacy

Key Technical Accomplishment

- Success metric: Design a PT-symmetric quantum read-write memory (storage time > 10 minutes)
- Key finding: PT-symmetric storage does not work in the quantum regime

How does this engage Sandia missions?

- Aligns with Sandia QIS (Quantum Information Science) strategy
  - Heterogeneous integration of long-term read-write quantum memory provides a capability critical for building a viable quantum computer
  - Would massively increase quantum system efficiency by reducing error correction overhead

Plans for follow-on and partnerships?

- Develop idea of long-term quantum memory using topological edge state of superconducting nanowire
  - Build partnerships with universities and Sandia experimentalists (e.g., Wei Pan (8342)) to write joint experiment-theory proposals
  - Timeline for future project: ~2 years

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